"Modeling Commercial Turbofan Engine Icing Risk with Ice Crystal Ingestion"
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Engine Icing Working Group

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Engine Icing Technical Challenge

Modeling Commercial Turbofan Engine Icing Risk with Ice Crystal Ingestion

The Phenomenon of
Jet Engine Icing

Researchers are exploring the theory that flight into certain kinds of storm clouds might cause ice to build up inside the core of an airplane's jet engine. Since 1988 there have been 153 engine power loss events* on a variety of airplane and engine types attributed to engine icing. A power loss event is a surge, stall, rollback or flameout of one or more engines. Events have occurred up to 41,000 feet and in different regions of the world. The majority occurred in descent and cruise. A multi-national research effort is now underway to identify exactly what causes this phenomenon and how to prevent it.

* Events reported through January 2010, FAA.

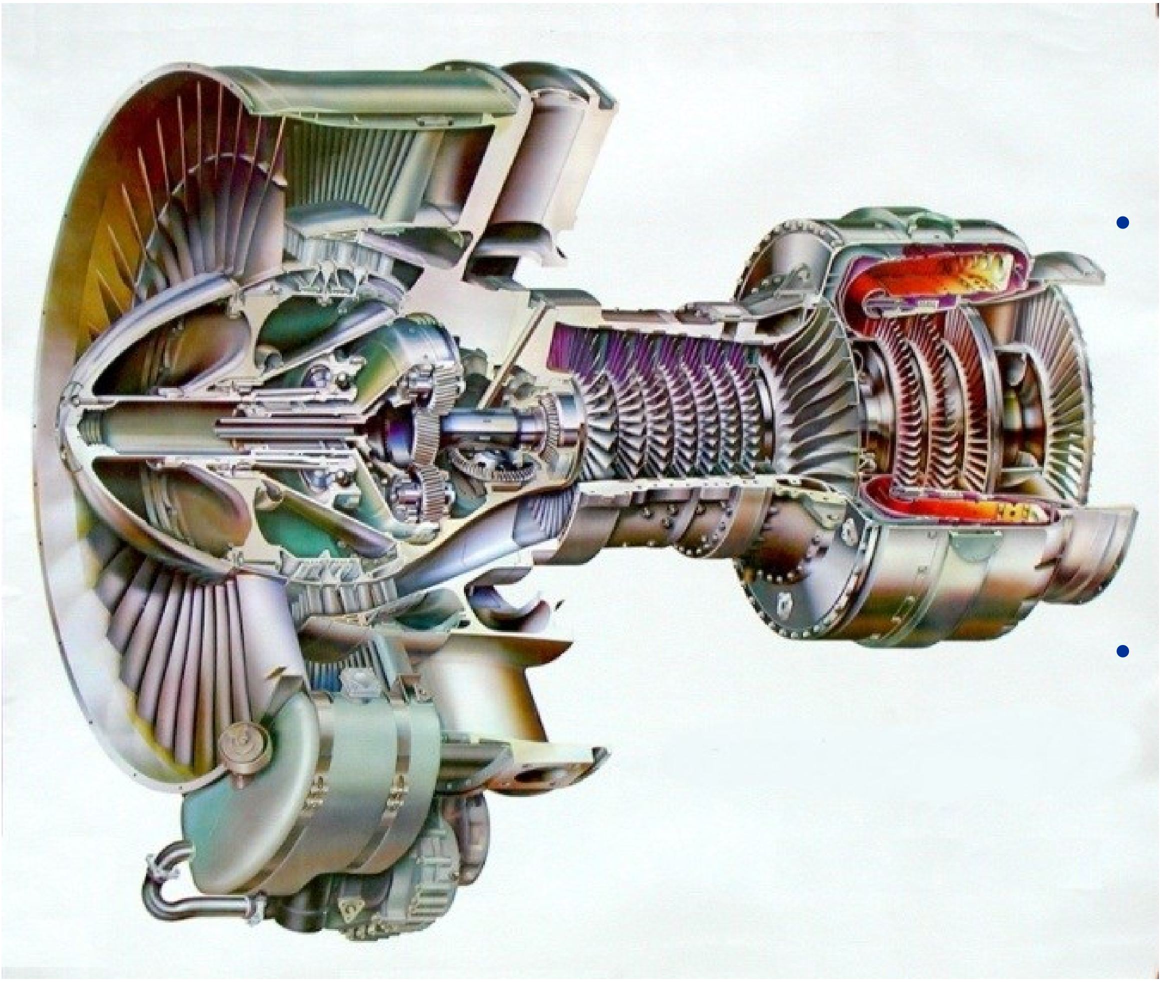
1 The belief is that jet engine icing can occur during flights into cold, high-altitude storm clouds holding massive quantities of small ice crystals. These conditions are not currently detectable on pilot radar. Ice crystals are drawn into the engine inlet where some are ingested with air that flows through the compressor and engine core; the rest are ejected with the air that bypasses the core.

2 As core flow is compressed, the air temperature rises and internal engine components warm above the ambient temperatures. Some ice crystals impact those components, forming a thin film of liquid water that captures additional ice crystals. This accumulation reduces the engine component temperatures so that ice can form.

3 At some point, ice breaks off from the components, which causes the engine to surge, stall, flame out or experience other malfunctions.

Graphic: NASA

Ice crystal ingestion causes ice accretion on LPC; resulting in loss of thrust control and engine rollback



- Engine roll back is an engine anomaly caused by ice accretion when encountering a high ice water content condition.
- Roll back is a loss of thrust event (i.e., commanded thrust does not equal actual thrust). Ice accretes on LPC restricting core airflow. Reduced air flow results in:
  - Increased fuel flow and increased high pressure turbine temperature
  - Reduced fan speed and thrust
- Turbofan engine experienced roll back events due to ice accretion from 1988 –1997 on regional aircraft. <u>The engine used for testing in the PSL was an old configuration, and all fielded engines have been upgraded to fix the roll back problem</u>

Computer flow codes used to perform engine icing risk analysis:

- **Engine Thermodynamic Cycle Analyses:**

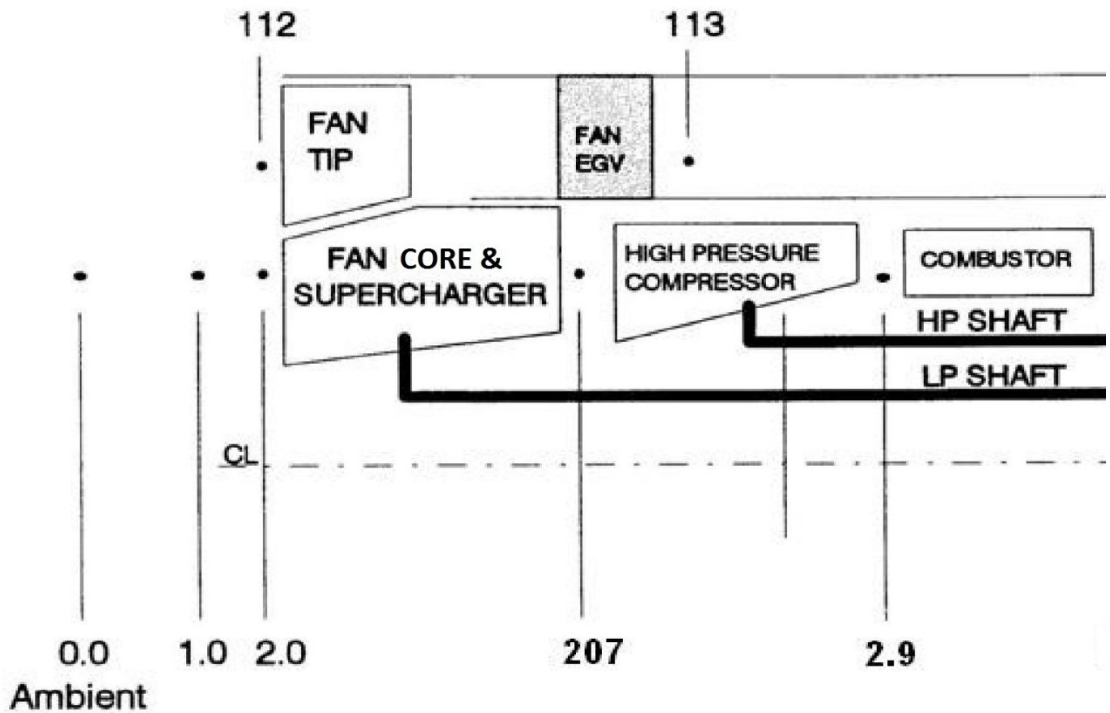
  - Numerical Propulsion System Simulation (NPSS)
  - Customer Deck (CD) supplied by engine manufacturer

- **Fan Core and Low Pressure Compressor Flow Analysis:**

  COMDES - Mean Line Compressor Steady-State Off-Design Flow Analysis Code:

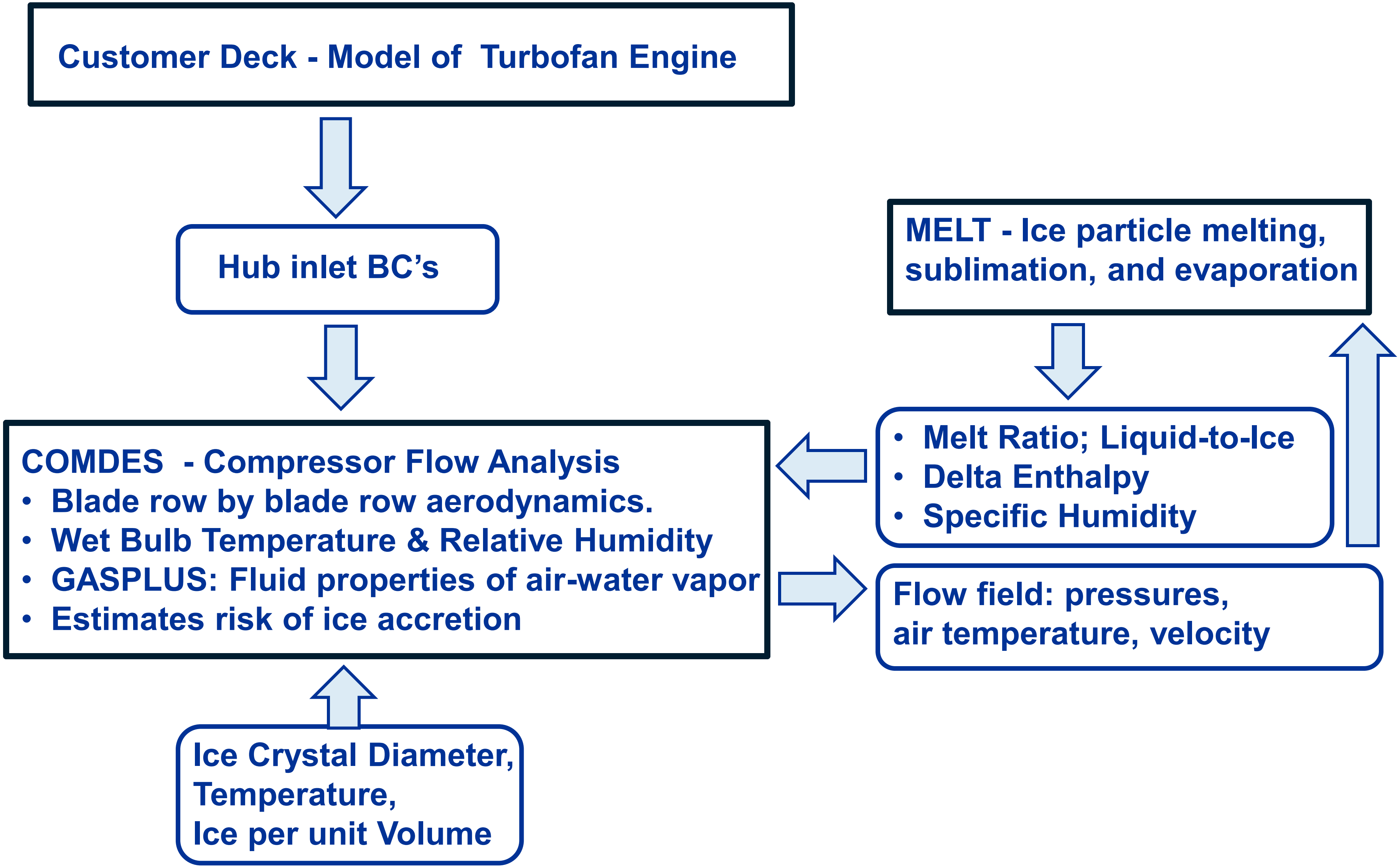
  - MELT, state of ice particle
  - GASPLUS, fluid properties of air-water vapor
  - Wet Bulb Temperature
  - Relative Humidity

CD Engine Thermodynamic Cycle Station Diagram



0.0	AMBIENT- FREE STREAM
1.0	STAGNATION CONDITIONS
112	FAN BYPASS INLET
113	FAN TIP COMPRESSOR EXIT
116	FAN NOZZLE INLET
118	FAN NOZZLE EXIT
2.0	FAN/ CORE INLET
207	SUPERCHARGER EXIT

Computational Process



Sources of heat that are modeled which affect the state of the ice particle:

- **Heated air due to energy addition by compression. This is a potential source of liquid water.**
- **Other sources of heat (or potential source of liquid water) are not modeled in this study.**

Computational flow code was used to assess the risk of ice accretion for two specific types of engine test data points:

- **Data points where engine ice accretion occurred**
- **Data point where engine ice accretion did not occur**

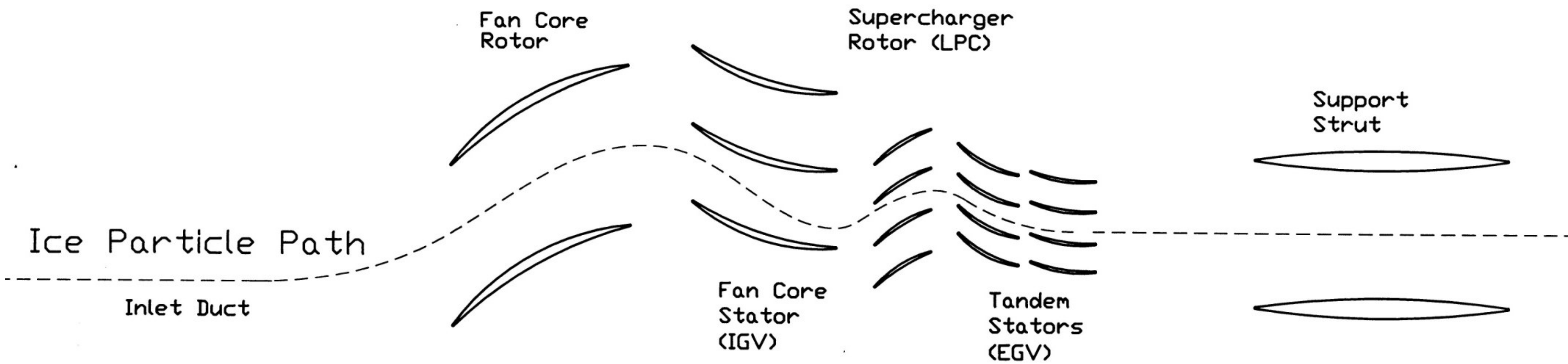
Determining Factors Considered for Icing Risk

Wet bulb temperature range - Based on analysis of the data taken in PSL, and analysis with the COMDES flow model, this indicator of ice accretion was in a narrow range of 7 degrees Rankine in the targeted area of the LPC.

Melt ratio – is has been demonstrated that a non-zero melt ratio due to heating by the air is a necessary condition for ice to accrete. Calculated by MELT code.

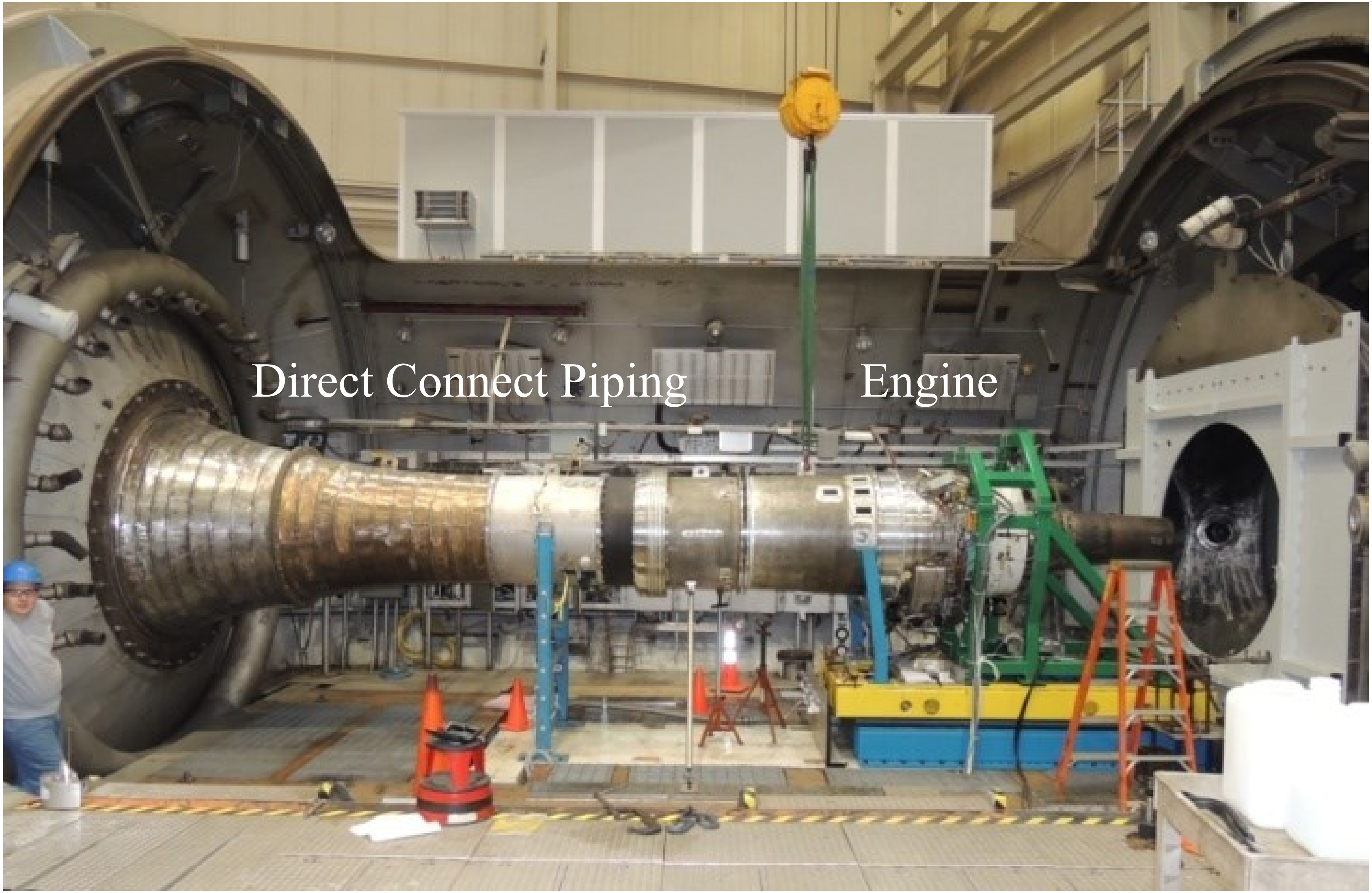
Particle size – since there is no particle breakup model in the computer analysis, the assumption is that the particle breaks up upon impact with the fan and LPC blading, and a particle size of 5 μm was selected since this size particle results in a computed non-zero melt ratio at the data points where there is a risk of ice accretion in the targeted area of the LPC.

MELT calculates the change in phase of an ice particle as it sublimates, melts, and evaporates in the flow path



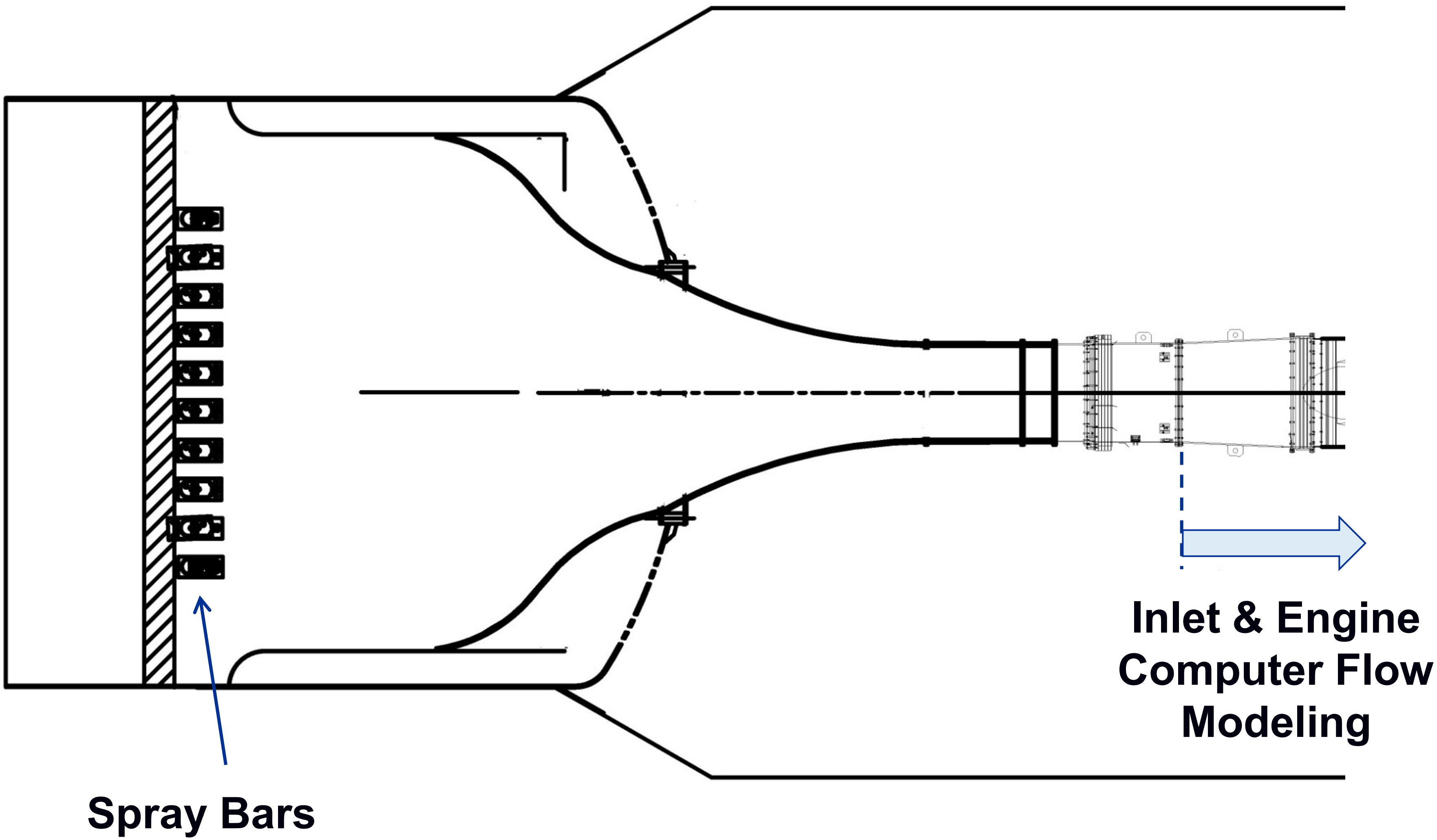
MELT leverages technologies from the LEWICE2D code.

Propulsion System Laboratory (PSL) Altitude Test Facility

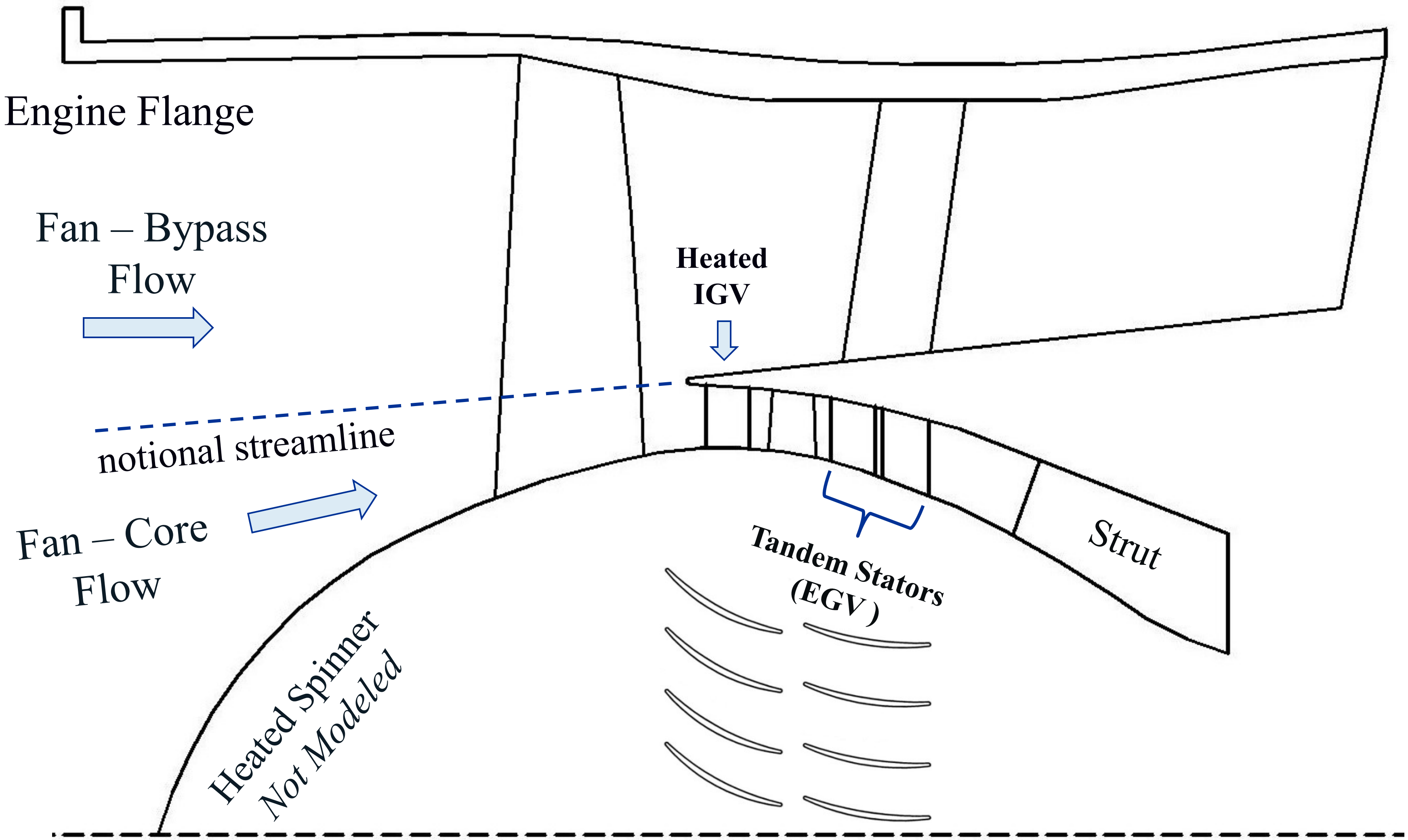


Direct Connect Inlet Duct

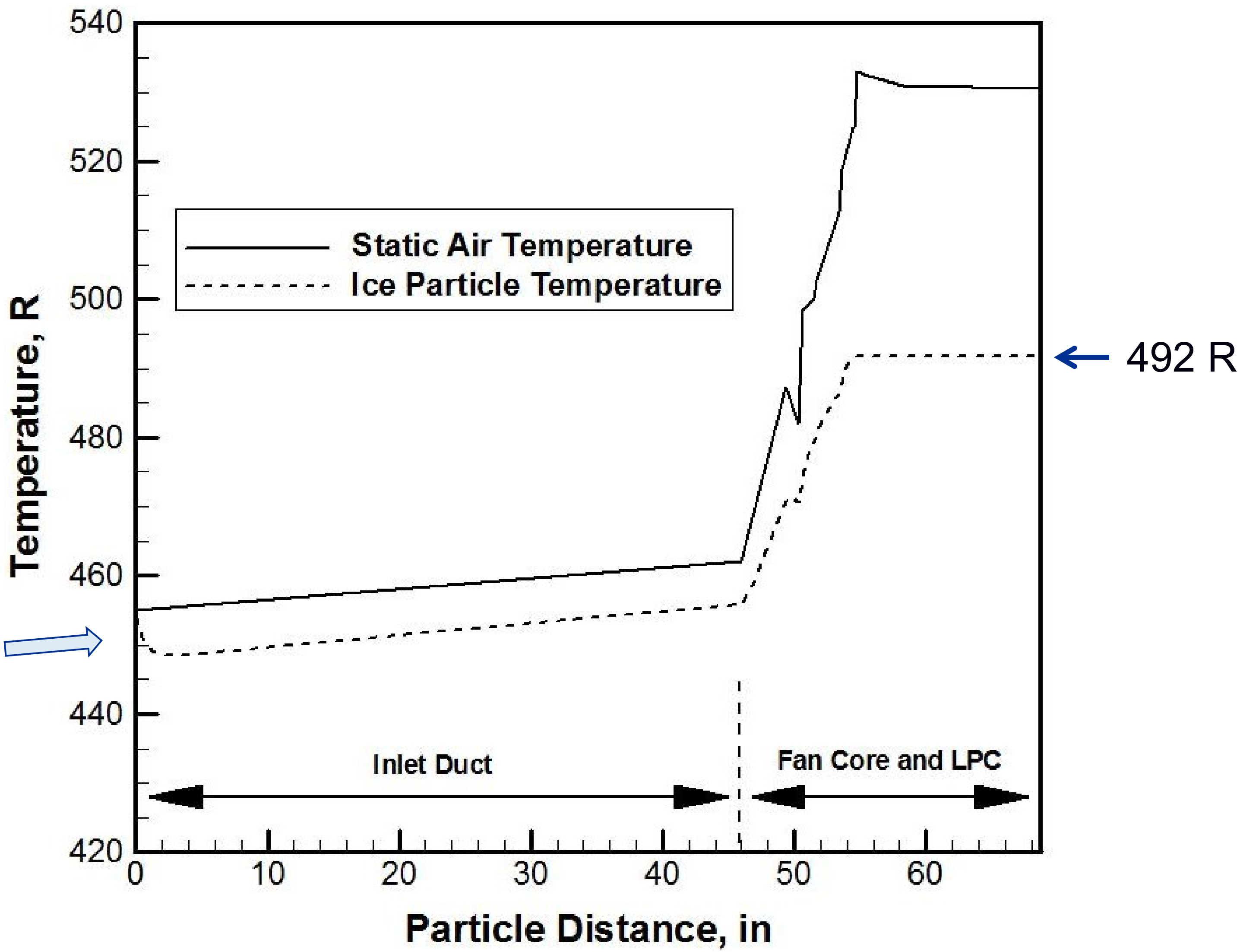
Connects the PSL Altitude Test Facility at the Engine Flange



Fan and Low Pressure Compressor Tested in the PSL with Ice Crystal Ingestion

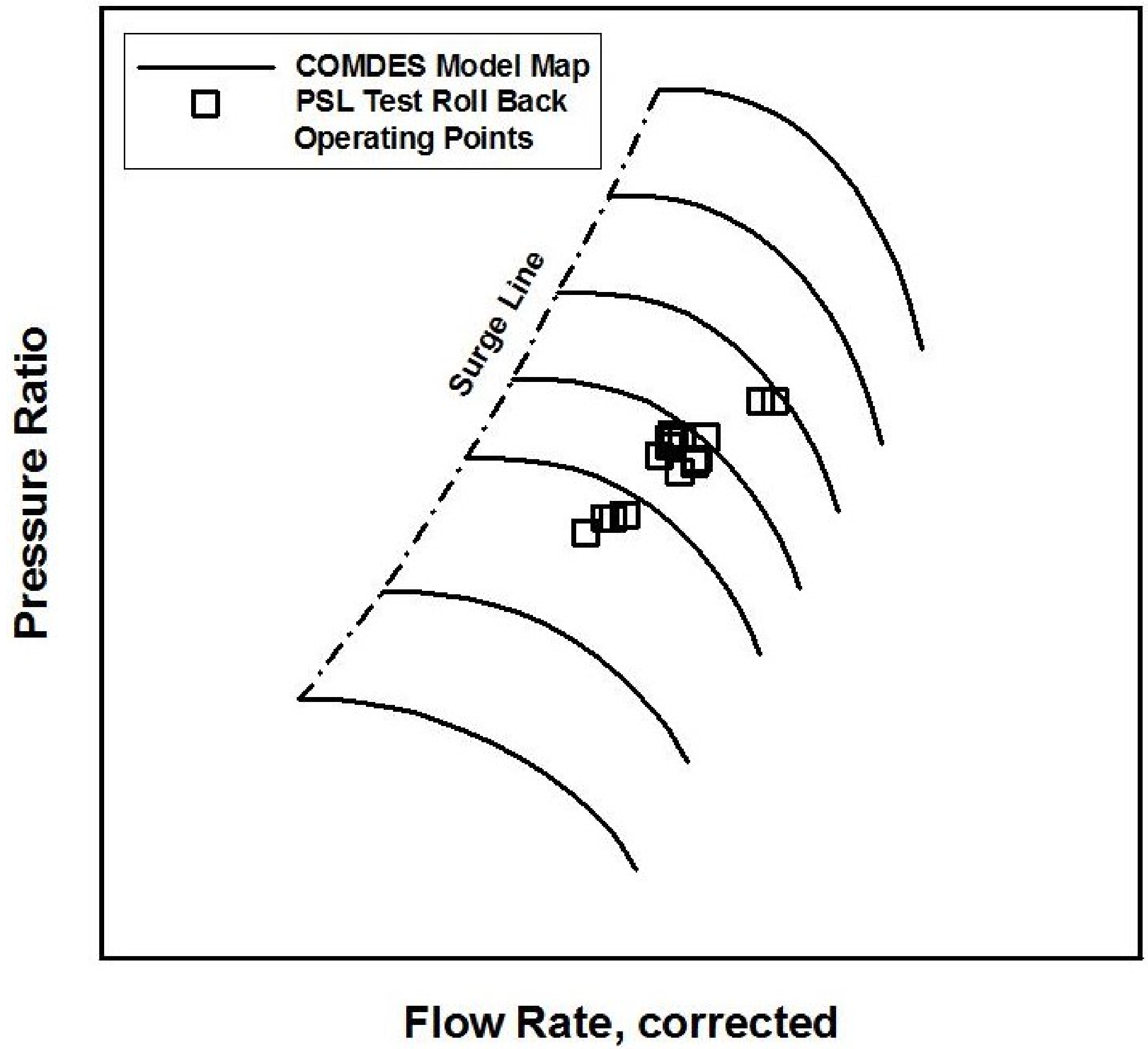


Modeled Temperature Rise of the Ice Crystal Particle & Air Through the Inlet Duct and Fan Core & LPC



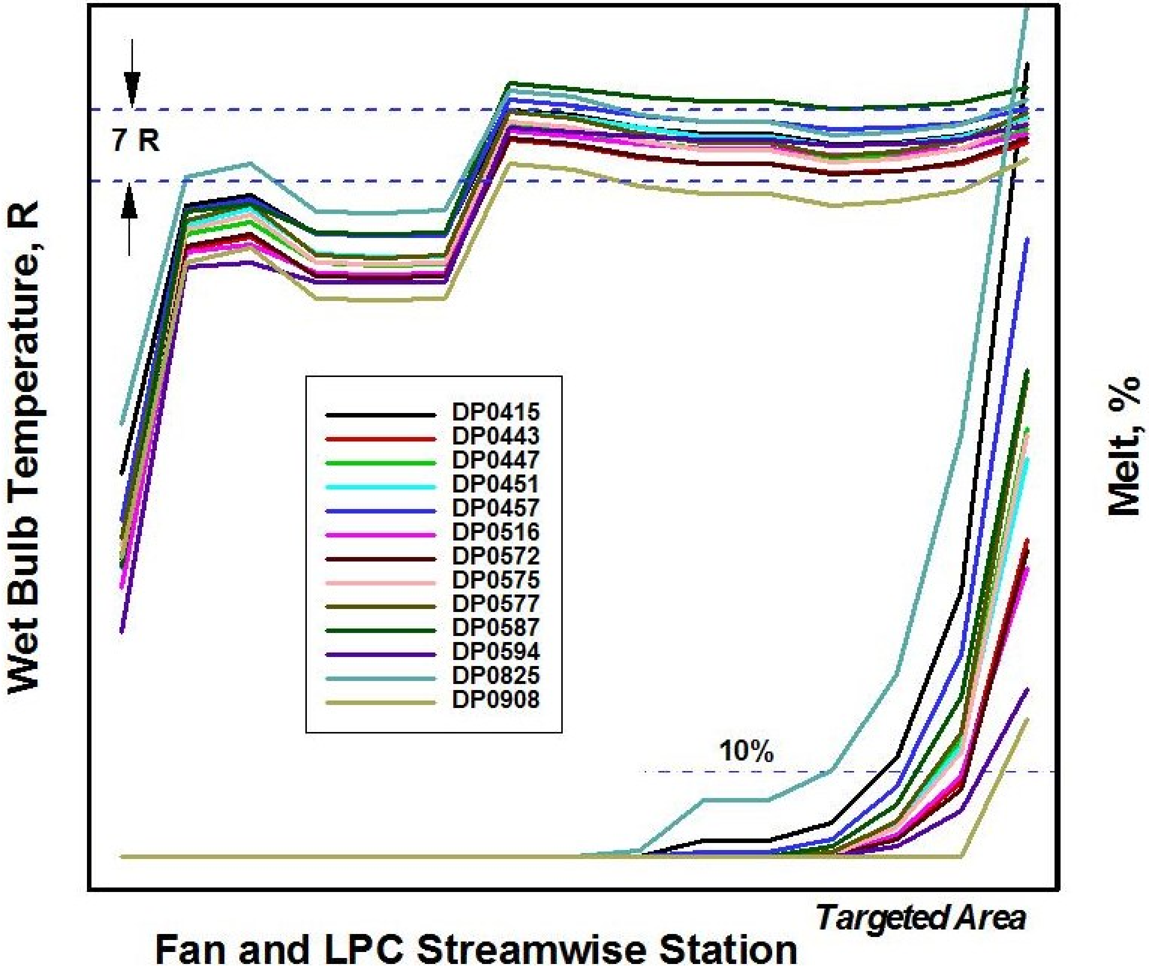
Ice particle attains thermodynamic equilibrium after entering inlet

Test data points plotted on the characteristic map where ice accretion occurred in the fan-core and LPC



Flow Analysis Results of Test Data Points with a Risk of Ice Accretion in the LPC

- Wet bulb temperature in the targeted area is in a narrow range: 7 R
- Melt ratio in the targeted area is non-zero



Example Data Point with Risk of Ice Accretion (DP0457)

DP0457 represents a point where there is a risk of ice accretion. This data point was at a cruise altitude condition. A comparison of the CD engine system model and the measured values for five engine parameters is as follows:

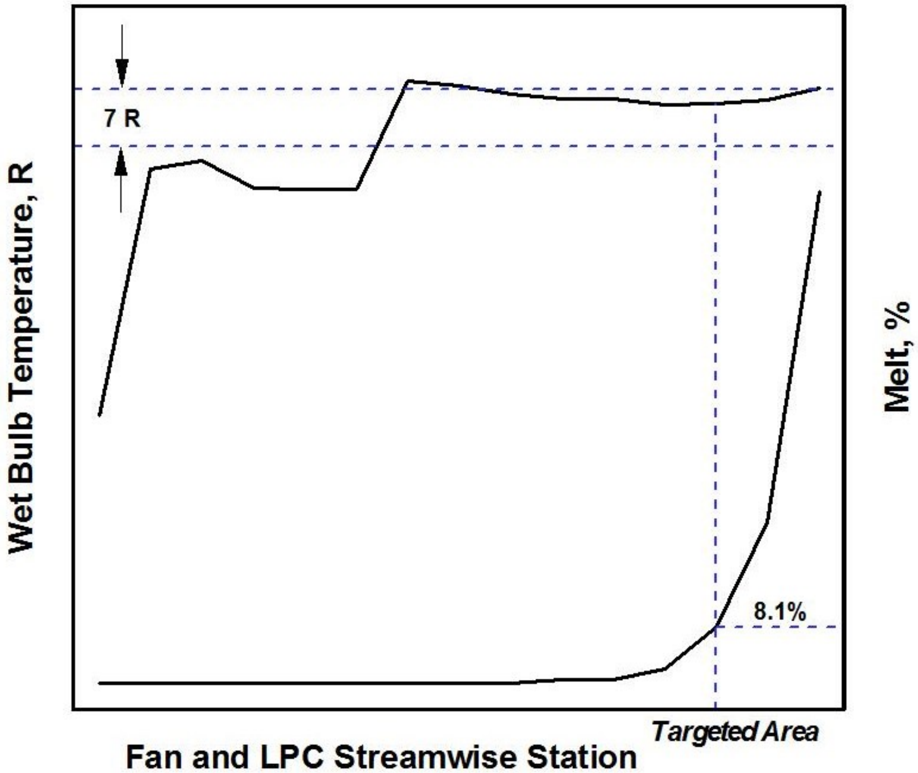
	% Delta
Air flow rate	**1.9**
Fuel Flow Rate	**1.5**
HPC Exit Temperature	**1.6**
HPC Exit Pressure	**0.6**
HPT Exit Temperature	**0.3**

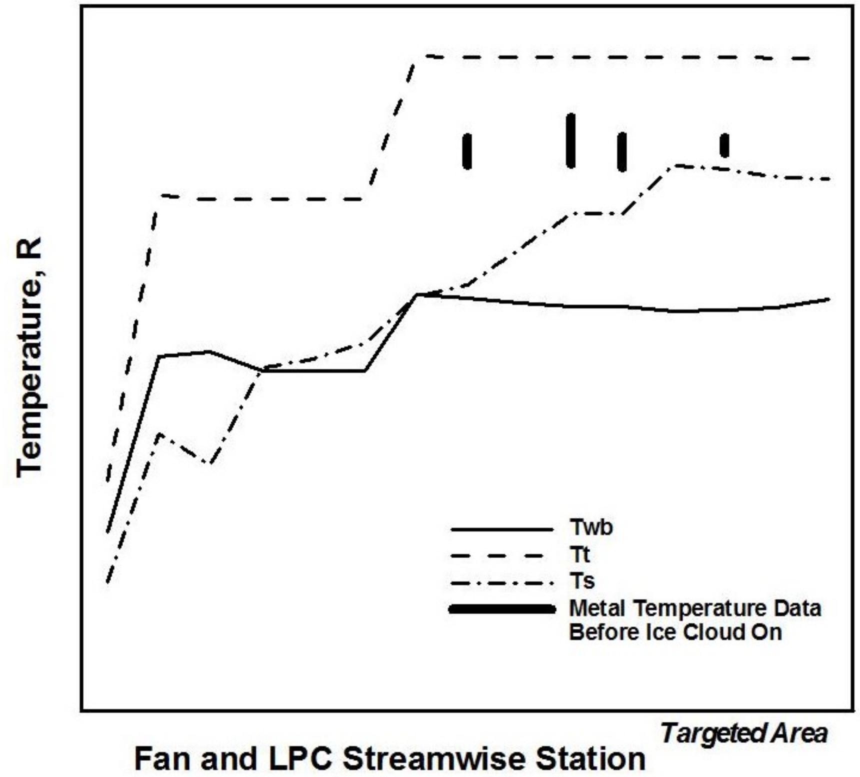
CD engine system model results were in good agreement with the PSL engine test data. Therefore the engine core inlet BCs provided to the compressor flow analysis code by the CD were considered acceptable.

Flow Analysis Results for DP0457; Risk of Ice Accretion

- T wet bulb falls within the 7 degree range.
- High melt ratio at the targeted area.

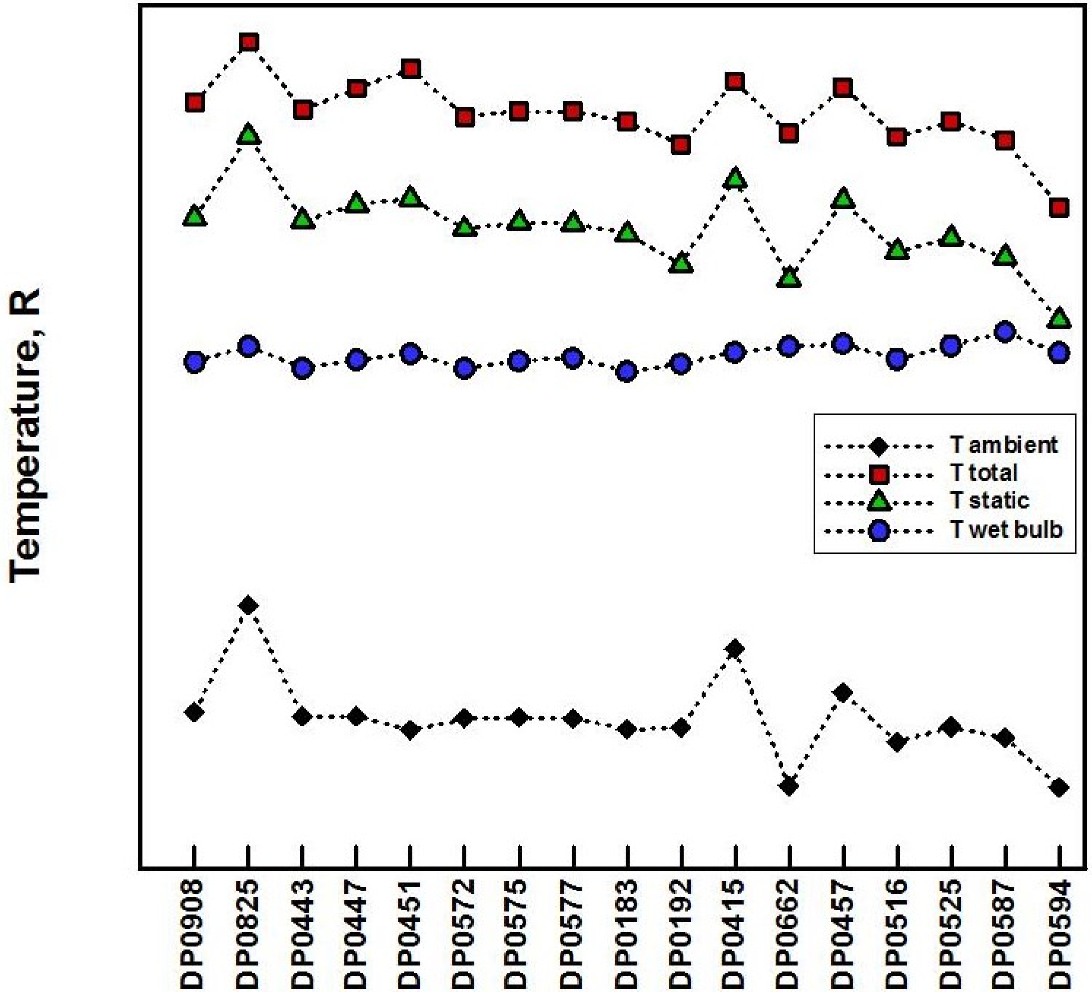
Calculated high total and static Temperatures; Promotes ice melting





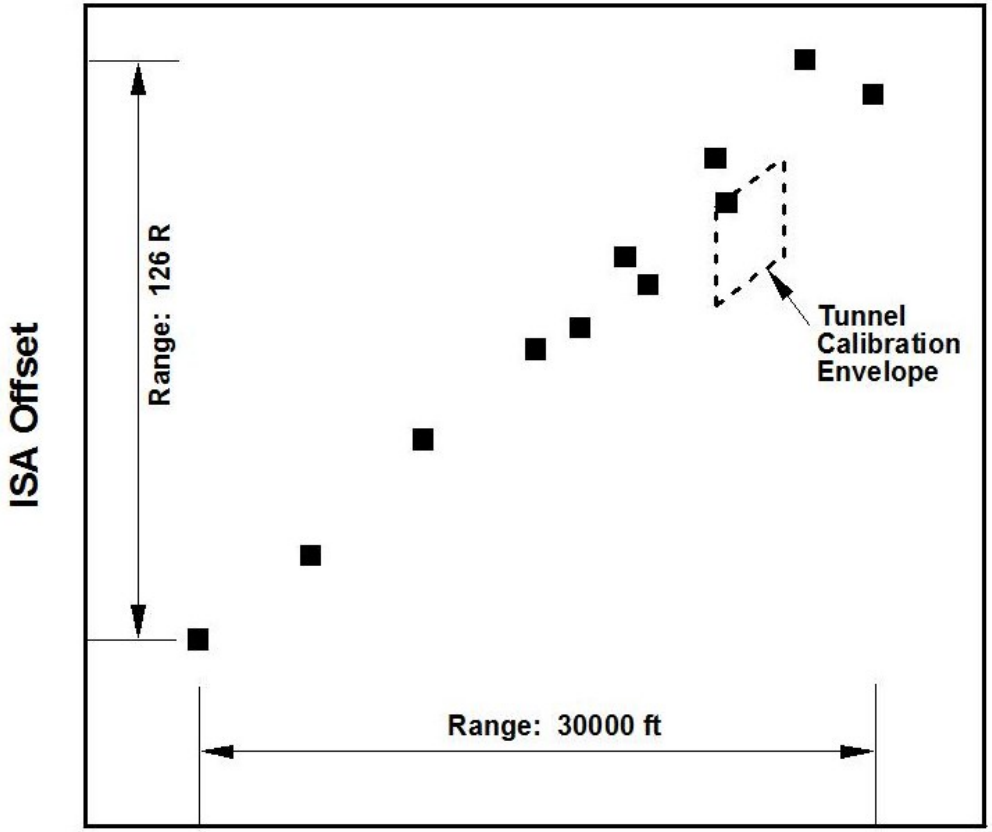
Thermocouple readings indicate metal temperatures are between the calculated values of air static and total temperatures. This indicates the air temperature calculations are reasonable.

Calculated static, total and wet bulb temperatures at the targeted area, for the engine data points with a risk of ice accretion, and the ambient temperature at engine inlet.



	Delta, R
T total	27.8
T static	31.0
T wet bulb	**6.7**
T ambient	30.5

Inlet Temperature Offset from ISA for Engine Data Points with a Risk of Ice Accretion vs. Altitude



The PSL tunnel was calibrated to produce ice crystals in a narrow range of conditions

- **The compressor flow analysis tool was calibrated at the engine data points that exhibited ice accretion within the tunnel calibration envelope.**
- **The analysis tool was then utilized to determine the required engine inlet temperature for ice accretion to occur at significantly lower altitudes.**
- **Subsequent testing in PSL confirmed the predicted risk of ice accretion at the lower altitudes.**

Example: Data Point with No Risk of Ice Accretion (DP0902)

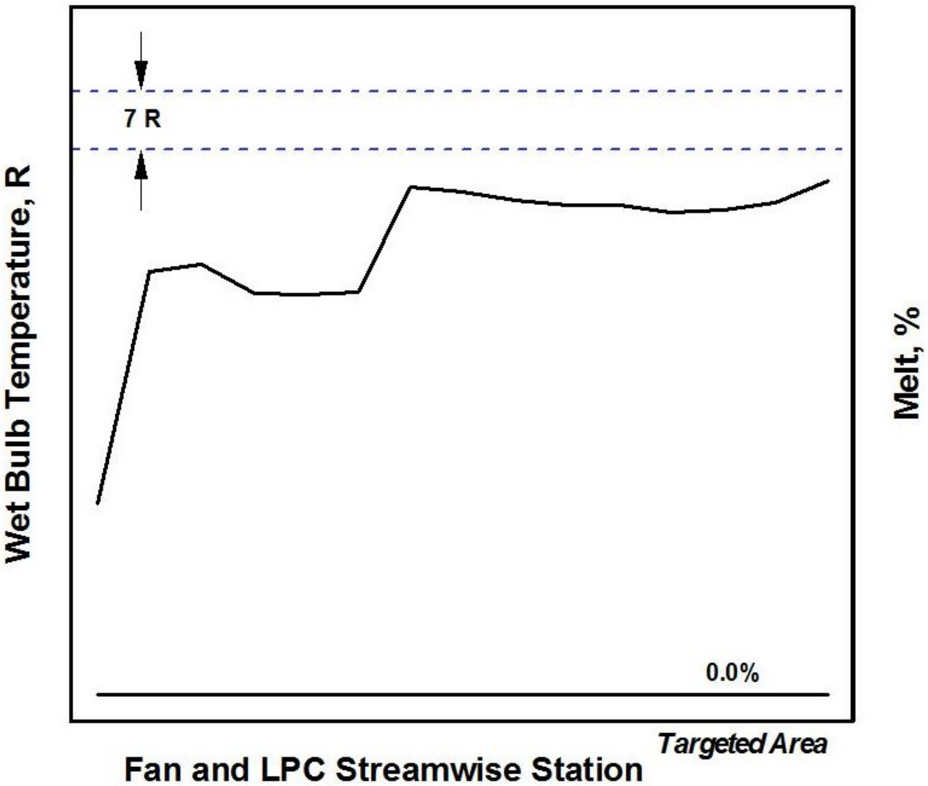
The engine did not have a risk of ice accretion at this data point. This data point was taken at a high altitude at cruise. A comparison of the CD engine system model and the measured values for five parameters is as follows:

	% Delta
Air flow rate	**6.2**
Fuel Flow Rate	**-0.1**
HPC Exit Temperature	**1.6**
HPC Exit Pressure	**0.2**
HPT Exit Temperature	**-0.1**

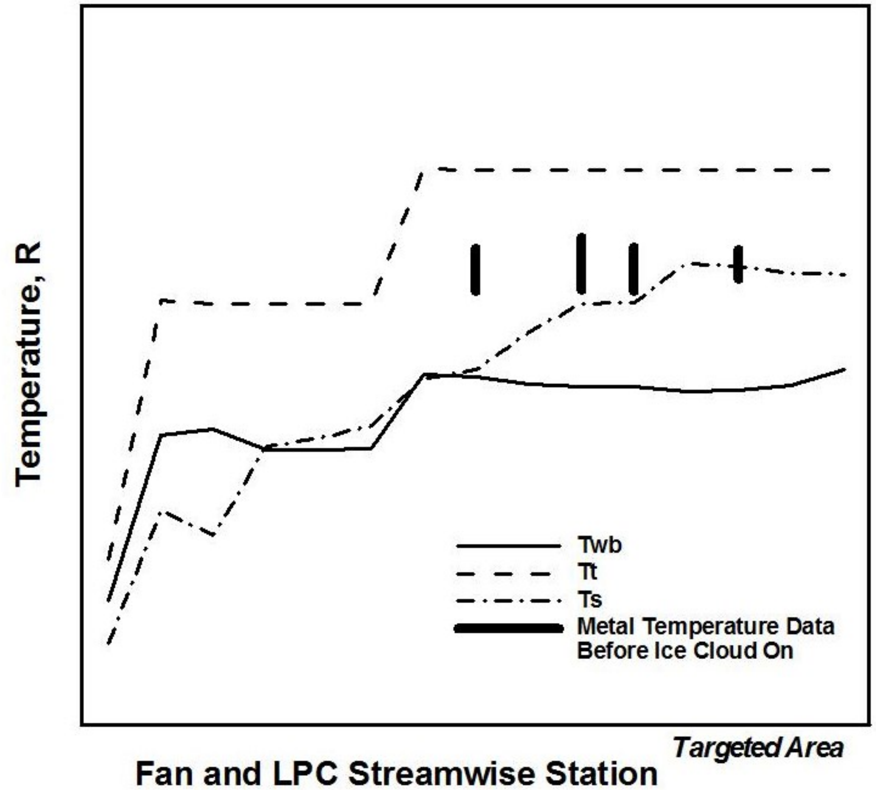
CD engine system model results were in good agreement with the PSL engine test data, except for the air flow (far from choke). Therefore the engine core inlet BCs provided to the compressor flow analysis code by the CD were considered acceptable.

Flow Analysis Results of Data Point - DP0902; No Risk of Ice Accretion

- T wb does not fall within the 7 degree range
- Zero melt ratio at the targeted area.



Calculated static and total air temperatures were 15 and 20 R lower than at the ice accretion data point.



Thermocouple readings indicate metal temperatures are between the calculated values of air static and total temperatures. This indicates the air temperature calculations are reasonable.

Summary:

- Applied a system of flow analysis codes to obtain the flow field through the fan core and LPC to assess the risk of ice accretion on a turbine engine.

- An engine known to have experienced an icing event at high altitude was tested in the PSL while ingesting a cloud of ice crystals.

- The compressor flow analysis code was calibrated, with values for wet bulb temperature, and melt ratio, based on the flow simulation of the selected data points which experienced ice accretion.

- The computer tool was used to predict the engine operating points where there is a risk of ice accretion at lower altitudes. These points were successfully produced in the PSL experiment.

- This analysis focused on the source of liquid water due to the heating of the ice particle by the air through the heat of compression.

Conclusions:

- Risk of ice accretion was predicted by the computer model when the ice melt ratio due to heating from the air was non-zero, and the wet bulb temperature was in the narrow range of 7 Rankine in the targeted area.

- No risk of ice accretion was predicted by the computer model, and confirmed by testing, when there was zero melt ratio from the air, and the wet bulb temperature did not fall within the 7 Rankine range.

Future Work:

- Further analyses are necessary to include heat transfer from other sources within the engine to account for additional liquid water in the flow field.

- At several operating points where the engine appeared to have ice accretion, but then stabilized. These points need further study.

- Parametric blockage applied at the targeted area of the LPC to model the engine characteristics as ice accretes, using NPSS.

- Ice accretion rate is another parameter that needs investigation.

- Higher fidelity multi-physics flow analysis may be the next step to improve understanding of the accretion and growth rate in the vicinity of the targeted zone.